Time and Longitude: an unexpected affinity

by Marco Lisi

Time, the fourth dimension, is becoming increasingly important in all aspects of technology and science.

The generation and distribution of an accurate reference time is a strategic asset on which the most disparate applications depend: from financial transactions to broadband communications, from satellite navigation systems to large laboratories for basic physical research (the so-called "Big Physics ").

But time is also the dimension through which technology evolves (as, for example, in the case of Moore's law which describes the increase in complexity of integrated electronic circuits) and obsolescence spreads.

Obsolescence will be the great challenge, often ignored or underestimated, that the economically and technologically advanced societies of the world will have to face in the years to come. The more technology increases its evolutionary pace, the more things that surround us quickly become "old", as they are no longer able to interface with each other and be maintained.

Maintenance and updating of obsolete parts (the so-called "logistics") are essential aspects in the operational life of a system and both have to do with time.

The importance of a precise time reference in our society and economy

The determination and the accurate measurement of time are the basis of our technological civilization. The major advances in this field have taken place in the last century, with the invention of the quartz crystal oscillator in 1920 and the first atomic clocks in the 40s. Nowadays time measurement is by far the most accurate among the measures of other fundamental physical quantities. Even the measurement unit for lengths, once based on the mythical reference meter, a sample of Platinum-Iridium preserved in Paris, was internationally redefined in 1983 as "the length of the path covered by light in vacuum during a time interval equal to 1/299792458 of a second ".

The second (symbol "s") is the unit of measurement of the official time in the International System of Units (SI). Its name comes simply from the second division of the hour, while the minute is the first. The second was originally defined as the 86400-th part of the mean solar day, i.e., the average, taken over a year, of the solar day, defined as the time interval elapsing between two successive passages of the Sun on the same meridian.

In 1884 the Greenwich Mean Time (GMT) was officially established as the international standard of time, defined as the mean solar time at the meridian passing through the Royal Observatory in Greenwich (England).

GMT calculates the time in each of the 24 zones (time zones) into which the earth's surface has been divided. The time decreases by one hour for each area west of Greenwich, and increases by one hour going east. GMT is also defined as "Z" time, or, in the phonetic alphabet, "Zulu" time. The time standard underlying the definition of GMT was maintained until astronomers discovered that the mean solar day was not constant, due to the slow (but continuous) slowdown of the Earth's rotation around its axis. This phenomenon is essentially linked to the braking action of the tides. It was then decided to refer the average solar day to a specific date, that of January 1, 1900. This solution was very impractical since it is not possible to go back in time and measure the duration of that particular day.

In 1967 a new definition of the second was proposed, based on the motion of precession of the isotope 133 of Cesium. The second is now defined as the time interval equal to 9192631770 cycles of the vibration of Cesium 133. This definition allows scientists anywhere in the world to reconstruct the duration of the second with equal precision and the concept of International Atomic Time or TAI is based on it.

The first atomic clock was developed in 1949 and was based on an absorption line of the ammonia molecule. The cesium clock, developed at the legendary NIST (National Institute of Standards and Technology) in Boulder, Colorado, can keep time with an accuracy better than one second in six million years. It was precisely the extreme accuracy of atomic clocks that led to the adoption of atomic time as an official reference worldwide. However, a new problem was been indirectly generated: the discrepancy between the international reference of time, based as mentioned on atomic clocks, and the average solar time. An average solar year increases by about 0.8 seconds per century (i.e., about an hour every 450,000 years). Consequently, universal time accumulates a delay of approximately 1 second every 500 days compared to international atomic time.

This means that our distant great-grandchildren, in the distant future just 50,000 years from now, would read "noon" on their atomic clocks, even though they are actually in the middle of the night. To overcome this and many other more serious drawbacks, the concept of Universal Coordinated Time (UTC) was introduced in 1972, which definitively replaced GMT.

In the short term, UTC essentially coincides with atomic time (called International Atomic Time, or TAI); when the difference between UTC and TAI approaches one second (this occurs approximately every 500 days), a fictitious second, called "leap second", is introduced.

In this way, the two time-scales, TAI and UTC, are kept within a maximum discrepancy of 0.9 seconds.

UTC ("Universal Coordinated Time"), defined by the historic "Bureau International des Poids et Mesures" (BIPM) in Sevres

Fig. 1 - UTC and critical infrastructures.

Fig. 2 - Stonehenge, a prehistoric astronomical observatory.

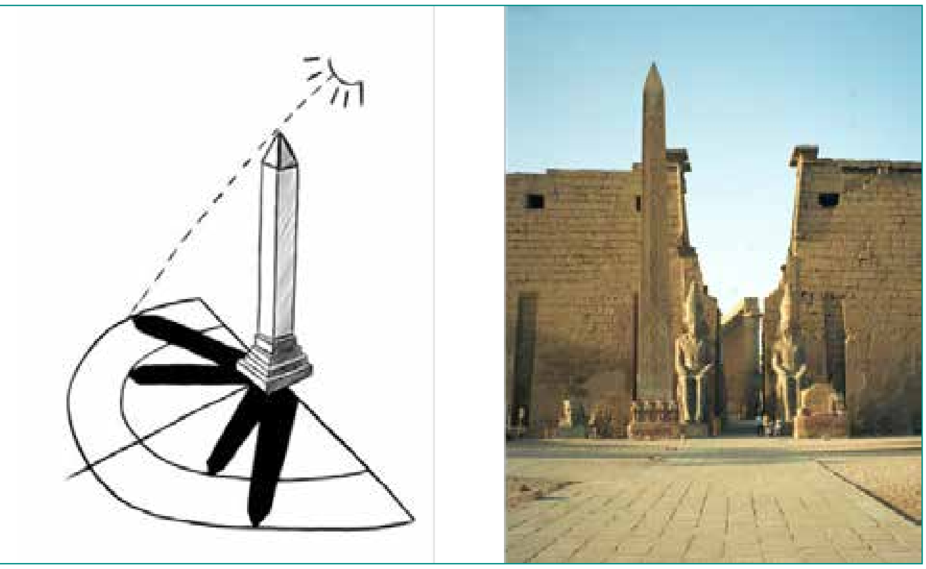

Fig. 3 - Ancient Egyptian stone obelisks.

(Paris), is since 1972 the legal basis for the measurement of time in the world, permanently replacing the old GMT. It is derived from TAI, from which it differs only by an integer number of seconds. TAI is in turn calculated by BIPM from data of more than 200 atomic clocks located in metrology institutes in more than 30 countries over the world.
But why is it so important to have an accurate and unambiguous definition of time?
It is a matter not only for scientists and experts. A universally recognized and very accurate reference time is in fact at the base of most infrastructures of our society (figure 1).
All cellular and wireless networks, for example, are based on careful synchronization of their nodes and base stations (obtained receiving GNSS signals, as we will see). The same is true for electric power distribution networks. Surprisingly, even financial transactions, banking, and stock markets all depend on an accurate time reference, given the extreme volatility in equity and currency markets, whose quotations might vary within a few microseconds.

Time and its measurement

The history of the measurement of time is as old as the history of human civilization.
In prehistoric England, the megalithic monument of Stonehenge seems to have been a sophisticated astronomical observatory to determine the length of the seasons and the date of the equinoxes (figure 2).
Already in 3500 BC the ancient Egyptians invented the sundial and erected stone obelisks throughout their country which had the primary purpose of marking the movement of the sun with their shadow and, therefore, the passage of time (figure 3).
In ancient Roman times and up until late in the Medieval Age, sundials, marked candles, water and sand hourglasses were used to measure time (figure 4).
A milestone in the history of the measurement of time was, in more recent times, Galileo's discovery, in 1583, of the constancy of the pendulum swing period, on which all mechanical clocks are based (figure 5).
In 1656 Christiaan Huygens, Dutch mathematician, astronomer, and physicist (famous among other things for having defined the principle of diffraction that bears his name) designed the first weight-wound pendulum clock, which deviated by ten minutes a day (figure 6).
But the major impetus for the development of ever more accurate techniques for measuring time came from the need to determine one's position (particularly longitude) aboard a ship in the open sea. From then on, time and positioning became irreversibly connected.

"Longitude problem" and measurement of time

The latitude and longitude coordinate system is commonly used to determine and describe one's position on Earth's surface and it was also known by astronomers

Fig. 4 - Roman and Medieval time measurement methods.

and navigators since the Greek and Roman times.
Determining latitude north or south with respect to the equator posed no major problems: it could be calculated through angular measurements of the sun and stars made with relatively simple instruments.
Measuring longitude, that is, identifying the east-west position on Earth between meridians, lines running from pole to pole, was a completely different story. Longitude was far more difficult than latitude to measure by astronomical observation.
Because of the Earth's rotation, the difference in longitude between two locations is equivalent to the difference in their local times: one degree of longitude equals a four-minute time difference, and 15 degrees is equal to one hour (making 360 degrees, or 24 hours, in total).
While a sextant with which to determine the height of the sun at noon was sufficient to determine one's latitude, the determination of longitude, due to the earth's rotation, required the use of both the sextant and a very precise clock.
Several methods had been proposed over the centuries by scientists and astronomers (including Galileo and Newton), all based on the observation of specific astronomical events, such as lunar eclipses.
All these methods turned out to be rather cumbersome and inaccurate by several hundred kilometers.
Even Christopher Columbus made two attempts to use lunar eclipses to discover his longitude, during his voyages to the New World, but his results were affected by large errors.
The lack of an accurate longitude determination method created innumerable problems (at times, real disasters) for sailors of

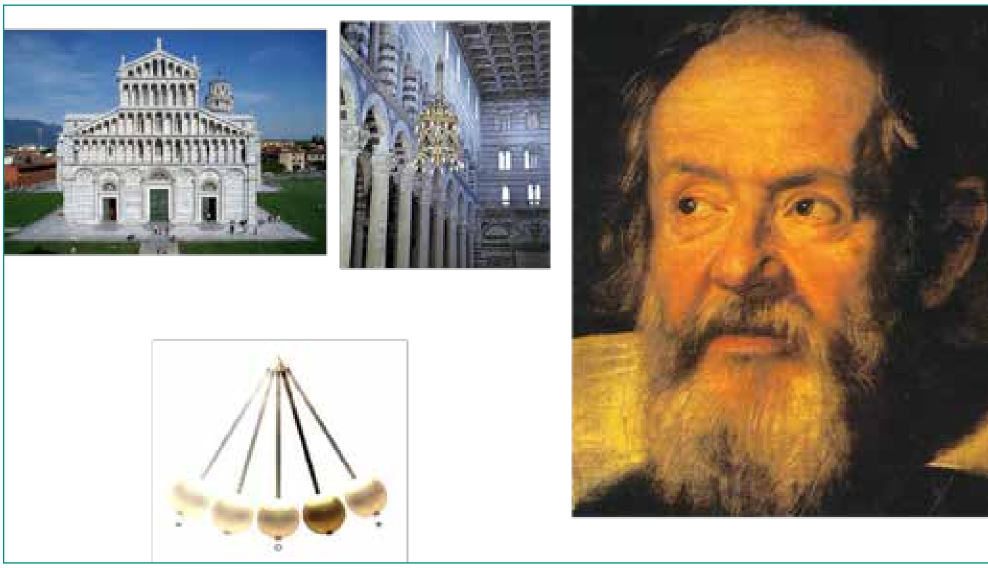

Fig. 5 - Galileo Galilei discovered in 1581 the isochronism of the pendulum.

the 15th and 16th centuries.
At the beginning of the eighteenth century, with the rapid growth of maritime traffic, a sense of urgency had arisen. The search for longitude cast a shadow over the life of every man at sea, and the safety of every vessel and merchant ship.
The exact measurement of longitude seemed at that time an impossible dream, a sort of perpetual motion machine.
There was a need for an instrument that recorded the time (at the place of departure) with the utmost precision during long sea voyages, despite the movement of the ship and the adverse climatic conditions of alternating hot and cold, humid and dry.
On the other hand, seventeenth-century and early eighteenth-century clocks were crude devices that usually lost or gained up to a quarter of an hour a day.
The "longitude problem" however became so serious that in 1714 the British Parliament formed a group of well-known scientists to study the solution, the "Board of Longitude". The Board offered twenty thousand pounds, equivalent to more than three million pounds today, to anyone who could find a way to determine the longitude of a ship on the open sea with accuracy within one-half of a degree (thirty nautical miles, about

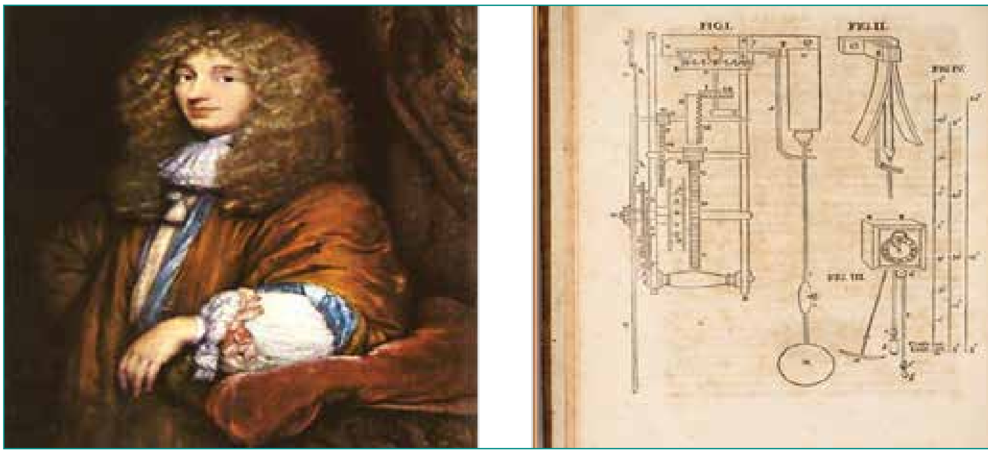

Fig. 6 - Christiaan Huygens and the first pendulum clock.

Figure 7: Right: John Harrison – Left (clockwise): H1 thru H4 Harrison's chronometers

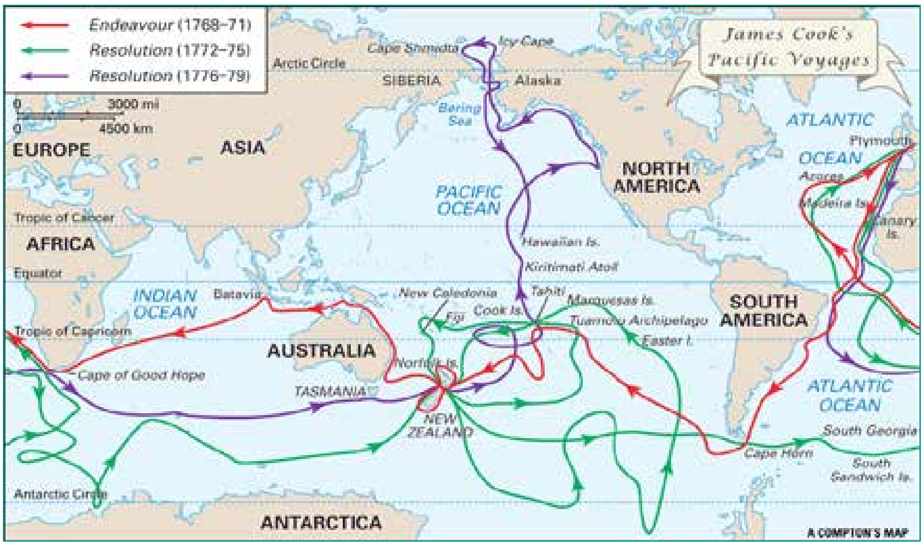

Fig. 8 - James Cook's Pacific Voyages.

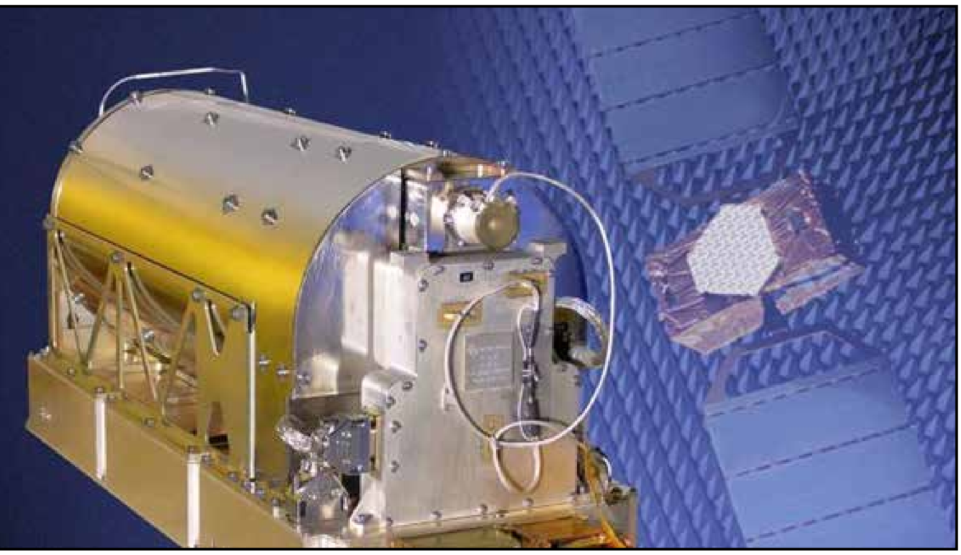

Fig. 9 - Galileo Passive Hydrogen Maser (PHM) clock.

fifty-five kilometers, at the equator).
The approach was successful, despite the many (and often completely crazy) proposals. In fact, in 1761, a self-educated Yorkshire carpenter and amateur clock-maker named John Harrison built a special mechanical clock to be loaded on board ships, called the "marine chronometer", capable of losing or gaining no more than one second per day (an incredible accuracy for that time) (figure 7).
Harrison did not receive the prize from the Board until after fighting for his reward, finally receiving payment in 1773, after the intervention of the British parliament.
And it was thanks to a copy of Harrison's H4 chronometer that Captain James Cook made his second and third legendary explorations of Polynesia and the Pacific islands on board the HMS Resolution (figure 8).
A copy of the H4 chronometer was also used in 1787 by Lieutenant William Bligh, commander of the famous HMS Bounty, but it was retained by Fletcher Christian following his mutiny. It was later recovered in Pitcairn Island to eventually reach the National Maritime Museum in London.

GNSS and Timing

An extremely accurate UTC reference is today provided worldwide by satellite navigation systems (GNSS) such as GPS (Global Positioning System), GLONASS, Beidou, and the European Galileo system. They are systems of satellites orbiting around the Earth, each containing onboard extremely precise atomic clocks which are all synchronized to a system reference clock.
GNSS technologies are intrinsically linked to accurate timing.

This is because of the specific principle (trilateration) on which position determination is based, i.e., the method of measuring the distance of a user from each satellite, involving the measurement of the time delay experienced by the signal-in-space.
The most accurate and numerous atomic clocks around the world are those belonging to GNSS, thus contributing substantially to the derivation of TAI and UTC (figure 9).
UTC can be derived from the Galileo and GPS signals, through a series of corrections based on data provided by the signals themselves. The accuracy obtainable, even with very cheap commercial receivers (or in those integrated into our smartphones) is easily better than one microsecond.

KEYWORDS

GNSS; GPS; Galileo; GLONASS; Beidou; time; longitude; GMT; TAI; UTC;

ABSTRACT

To have an accurate and unambiguous definition of time is a matter not only for scientists and experts. A universally recognized and very accurate reference time is in fact at the base of most infrastructures of our society. All cellular and wireless networks, for example, are based on careful synchronization of their nodes and base stations (obtained receiving GNSS signals, as we will see). The same is true for electric power distribution networks. Surprisingly, even financial transactions and banking and stock markets all depend on an accurate time reference, given the extreme volatility in equity and currency markets, whose quotations might vary within a few microseconds. The history of the measurement of time is as old as the history of human civilization. But the major impetus for the development of ever more accurate techniques for measuring time came from the need to determine one's position (particularly longitude) aboard a ship in the open sea. In 1761, a self-educated Yorkshire carpenter and amateur clock-maker named John Harrison built a special mechanical clock to be loaded on board ships, called the "marine chronometer", capable of losing or gaining no more than one second per day (an incredible accuracy for that time). From then on, time and positioning became irreversibly connected.

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